Design and Manufacturing of Lightweight Composite Structures Based on Continuous Fiber Reinforced Composites 3D Printing

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ABBREVIATION

Continuous Fiber Reinforced Composite Lightweight Structures : CFRCLSs

ABSTRACT

Resin matrix composite lightweight structure has the advantages of low density and high performance, for use in lightweight applications such as aerospace, high-speed trains, ships and others. However, the disadvantages of conventional forming processes, such as complex process, long process period and high cost, have limited the wide applications of resin matrix composite lightweight structure. 3D printing is a new forming process of parts, and it is possible to realize integrated manufacturing of high performance composite lightweight structure. This paper reviews the research status of resin matrix composite lightweight structure 3D printing, and meanwhile presents a new integrated manufacturing process of high performance resin matrix composite lightweight structure based on continuous fiber reinforced thermoplastic composites 3D printing.

Keywords: Continuous Fiber Reinforced Composite; Lightweight structure; 3D printing; Fiber reinforcement

1. Introduction

Composite lightweight structures an advanced design ideal for composite material, which makes full use of the material characteristics and structural advantages to achieve the best performance of the part[1-3].In recent years, there has been a growing interest in manufacturing and charactering the properties of continuous fiber reinforced composite lightweight structures (CFRCLSs) [4-6]. The advantages of CFRCLSs include great stiffness to weight ratios, improved fatigue life, steadiness under compressive forces and good design ability. These benefits determine the fact that the use of continuous fiber reinforced composites has improved ominously in a wide range of structural applications such as aerospace, high-speed trains, ships and others.

Recently, development of new fabrication process of CFRCLSs has been attracted many research activities. Finnegan et al. [7] used a snap-fitting method to produce carbon fiber reinforced composite pyramidal truss cores, and developed a robust face-sheet/truss joint design to suppress truss– face sheet node fracture. Wu et al. [5]fabricated the continuous fiber reinforced composite pyramidal lattice truss core sandwich by the hot-press molding technique and interlocking method. Rejab et al. [6] used a hot press moulding technique to fabricate the continuous fiber reinforced composite corrugated-cores, and then bonded to face sheets based on the same material, to produce a range of lightweight sandwich panels. Jishi et al. [8]manufactured a range of lattice structures, based on carbon fiber reinforced epoxy composite, using the VARTM manufacturing technique. These fabrication processes usually involve three steps. First, the prepreg is prepared by deposition or impregnation. Second, processes like vacuum forming, filament winding, pultrusion, bladder-assisted molding and compress have been used in fabrication of simple shape continuous fiber reinforced composite parts. Finally, the CFRCLS is prepared by machining, assembling and cementation. These fabrication processes of CFRCLSs are difficult and even impossible to fabricate complex composite component. Also, uncontrollable forming quality and low degree of automation are limitations of the wide industrial applications of CFRCLSs. Innovation on the fabrication process is critical and urgent to the future development and application of CFRCLSs.

3D printing rapidly grew in the past decade, and has the advantages of short production cycle, low cost, and high automation. This unique manufacturing method can realize the fabrication of parts with arbitrary shapes, greatly expanding the design space and providing a powerful tool for the preparation of new structures and materials[9,10].However, researches related with 3D printing of composite lightweight structures, especially in CFRCLSs, have been seldom found. In 2014, Harvard University[11] developed a new epoxy-based ink that enables 3Dprinting of cellular composites with controlled alignment of multi-scale, high aspect ratio short fiber reinforcement to create hierarchical structures inspired by balsa wood. Using this unique combination of hierarchical inks and 3D printing, they created lightweight, wood-inspired cellular composites that cannot be fabricated any other way. These materials exhibit Young's modulus values that are an order of magnitude higher than those obtained by thermoplastics and photocurable resins developed for commercial 3D printing methods, while retaining comparable strength. In the same year, applying 3D laser lithography, Karlsruhe Institute of Technology[12] produced and characterized micro-truss and -shell structures made from alumina–polymer composite. Size-dependent strengthening of alumina shells has been observed, particularly when applied with a characteristic thickness below 100 nm. The presented artificial cellular materials reach compressive strengths up to 280 MPa with densities well below 1000 kg/m^3.At present, there is no research on the integrated manufacturing of CFRCLSs using 3D printing. The existing researches mainly focus on the integrated manufacturing of short fiber reinforced composites lightweight structures and micro-nano scale lightweight structures. The performance of short fibers on composites improved little compared with that of continuous fibers. The composite lightweight structure using micro-nano scale 3D printing can realize the fabrication of the structure form with excellent performance, but it has the disadvantages of long fabricating time, high cost, and being difficult to achieve manufacturing macro scale structures. This can't meet the needs of large parts in aerospace, automobile, etc.

The aim of the study presented here is to use continuous fiber reinforced thermoplastic composites 3D printing to realize the integrated manufacturing of CFRCLSs of varying complexity. Initial attention is given to path design method of complex configurations.

2. Equipment and material

2.1.1. Experimental platform

The 3D printing equipment for CFRCLSs was independently developed and set up in the present research, which consists of extrusion head, control system, building platform, X-Y motion mechanism, etc, as shown in Fig. 1a. In order to realize the manufacture of large lightweight structure, a 3D printing device based on material extrusion process was integrated on an industrial robot system, as shown in Fig. 1b. This system employed 6-degree of freedom robotic arm (MITSUBISHI RV-7F-1Q-S11) as the motion mechanism. The 3D printing module based on material extrusion technology was designed and assembled on the robotic arm as an end-effector. Fig. 1c shows the working process of the extrusion head, which receives thermoplastic polymer and continuous fiber to build a continuous fiber reinforced composite light structure part.

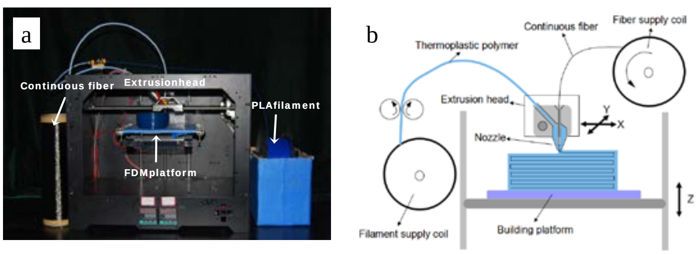

Fig. 1. Equipment and scheme of 3D printing for CFRCLSs, (a) the setup for the 3D printing of CFRCLSs, (b) scheme of the printing process [13].

2.1.2. Raw materials

In the present research, Kevlar® fiber (linear density of 145 dtex, density of 1440 Kg/m^3) from DuPont Corp. in U.S.A has been used as the reinforcement, and polylactide (PLA/1.75 mm, density of 1240 Kg/m^3) from FLASHFORGE Corp. in China has been used as the thermoplastic material.

3. Fabrication process

3.1.1. Structural design

To evaluate the structural performance of 3D printed CFRCLSs, a type of lightweight sandwich structure based on spline corrugated-core was designed and fabricated in this study, as shown in Fig. 2. This lightweight sandwich structure specimen was 60 mm in length (L), 60 mm in width (W) and 15 mm in thickness (H). The thickness of the sandwich core, corrugated wall and each of the two face sheets was 13 mm, 1mm and 1mm respectively. All the specimens were prepared on the aforementioned experimental equipment, as shown in Fig. 1a.

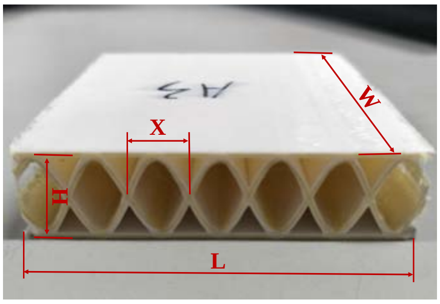

Fig. 2. Spline corrugated-cores sandwich structure.

3.1.2. Path design

Debonding failure between the core and face sheets is a popular failure mode of lightweight sandwich structure. In order to improve the mechanical properties of the lightweight structure, and to solve the problem of the forming of the CFRCLSs with complex shape, a new strategy based on 3D printing for the integration manufacturing of complex core and panel-core should be carefully conceived, studied and verified. Thermoplastic resin is characterized by melting after heating and curing after cooling, and the two methods of cross lap and panel-core lap were proposed. As shown in Fig. 3, path 2 is executed after the path 1 executed. When the nozzle passes through the lap joint, the resin at the lap joint is heated and fused, and the extruded silk material is adhered and solidified at the lap joint, so as to realize the integrated forming of the panel-core. The same principle is used to realize the integrated forming of complex core.

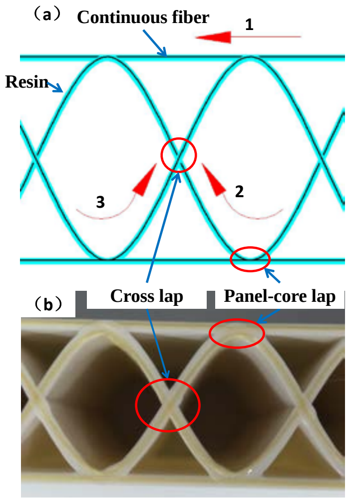

Fig. 3. Path planning. (a) Printing strategy. (b) Overlapping structure sample.

4. Experimental results and discussion

To evaluate the performance of 3D printed CFRCLSs, several measurements were conducted. Compressive strength was measured using universal testing machine (MTS 880/25t, MTS Corp., U.S.A) according to the standard of GB/T1453:2005. Quality of printed lightweight structure specimens was measured on the testing device (DX-300, QUNLONG Corp., China). The process of specimen compression is recorded by high-speed camera (Phantom Miro VRI-M310, AMETEK Corp., U.S.A). For each experimental group, five specimens were prepared to obtain an average value of the targeted properties.

A typical stress–strain trace following a compression test on the printed CFRCLSs is presented in Fig. 7(a). Upon loading, the specimen exhibits an initial non-linear response (point A to point B), which is possibly associated with the initial machine compliance. The specimen subsequently responds in a linear elastic (point B to point C) up to the maximum value in the trace. After reaching the peak stress, the corrugated-core was yielded as a consequence, the overall stiffness of the specimen decreased. The load required to further deform the sample gradually decreases due to the buckling of the corrugated-core (point C to point D).The response then becomes progressively non-linear (point D to point F),where the force drops slowly as the corrugated-core becomes stability due to the core is becoming more and more compact. In Region E to F, the corrugated-core is cracked. Finally, after F the corrugated-core has been completely densified, and stress rises with strain. The evidence from these tests on the printed CFRCLSs indicates that elastic buckling, plastic deformation and the fracture of corrugated-core are the dominant failure mode in this material.

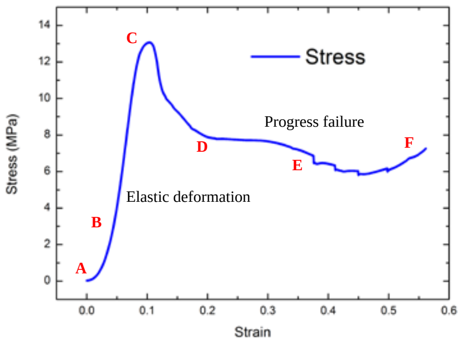

Fig. 4. Compression stress-strain curves.

5. Conclusions

The integrated manufacturing process based on continuous fiber reinforced thermoplastic composites 3D printing of CFRCLSs was proposed and studied in this paper. In this process, the two new path design strategy of cross lap and panel-core lap were proposed to fabricated the CFRCLSs with complex shape. With the optimized structure parameters and process parameters, 3D printed CFRCLSs with a fiber content of 11.5%vol can achieve the maximum compression strength of 17.17 MPa. This new and improved process has great potential in fabricating CFRCLSs with complex shape, high mechanical properties and multifunctional benefits.

Acknowledgments

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